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TEST EVALUATION OF VARIOUS ABLATIVE MATERIALS

Prepared by: Charles D. Reno
Charles D. Reno

Approved by: Jesse C. Jones
Jesse C. Jones
Chief, Thermochemical Test Branch

Approved by: Richard B. Ferguson for
Joseph G. Thibodaux, Jr.
Chief, Propulsion and Power Division

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MANNED SPACECRAFT CENTER

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TEST EVALUATION OF VARIOUS ABLATIVE MATERIALS FOR ROCKET ENGINE APPLICATION

INTRODUCTION

The Marquardt Corporation (TMC) supplied the Manned Spacecraft Center (MSC) with eighteen billets representing ten different ablative materials for a material evaluation test program. The objective of this test was to evaluate and compare the performance of various ablative materials for possible application in small, liquid bipropellant reaction control system (RCS) rocket engines.

The test program was conducted by the Thermochemical Test Section for the Auxiliary Propulsion Section of Energy Systems Branch, Propulsion and Energy Systems Division. The test was conducted at the interim Reaction Control Test Facility at Ellington Air Force Base, Texas, during the period from December 6, 1963, to January 4, 1964.

TEST EQUIPMENT DESCRIPTION

A special test (evaluator) engine, as shown in figures 1 and 2, was used to test the ablative material billets. This engine consists of an Advent 25-pound thrust engine injector, an injector adapter plate, an ablative chamber, and a water cooled throat section. The mating parts of the evaluator engine are sealed by "O" rings and held in compression by a bolt and spring arrangement. The injector head is a six-on-six multiple-point doublet with fuel supplied to the outer ring of injector tubes and oxidizer supplied to the inner ring. Propellant flow is controlled by two independent coaxial solenoid valves. The injector adapter is a circular steel plate on which the injector head is mounted. The adapter plate incorporates a small steel pre-combustion chamber which fits into a space formed by adjoining recesses in the adapter plate and billet. The water cooled nozzle section is a rectangular plate, fabricated from copper, and contains a converging-diverging throat of 0.336 inches diameter. Four 0.5 inch connections are provided for water inlet and outlet. The water flows in an annulus around the throat. The interior surface of the nozzle is coated with a Rokide thermal and oxidation resistant coating. The evaluator engine operating parameters are as follows:

Chamber pressure (Pc)	150 psia
Thrust (F), sea level	12 - 13 lbs
Propellants	Nitrogen Tetroxide and Aerozine 50
Fuel flow rate ($\dot{\omega}_F$)	.0234 lbs/sec.
Oxidizer flow rate ($\dot{\omega}_O$)	.0375 lbs/sec.
Oxidizer/fuel ratio (O/F)	1.6

Detailed performance of the evaluator engine with the various billets tested is shown in table 1.

The ablative billets, which make up the combustion chamber of the evaluator engine, are cylindrical, 4.50 inches outside diameter, 0.780 inches inside diameter, and 2.00 inches in length. The following ablative materials were tested:

a. MXS-51 (one billet tested) - A silica fiber fabric bonded by a snap cured phenolic resin, tape wound, with a laminate orientation of 60° to the axial centerline. This material permits fabrication of chambers without large pressure molding equipment.

b. MXSE-48 (two billets tested) - A silica fiber fabric bonded with a Buna-N modified phenolic resin, tape wound, with a laminate orientation of 60°. This material has a lower thermal conductivity and a higher resin content than straight silica-phenolic ablatives.

c. MX-2646 (three billets tested) - A high purity silica fiber fabric bonded with phenolic resin, tape wound, with a laminate orientation of 60°. One MX-2646 billet was not post-cured while the other two billets tested were subjected to different post-cure, time-temperature cycles. These post-cured billets were identified as MX-2646 "A" and MX-2646 "B".

d. MXR-42 (two billets tested) - A new experimental material which combines a highly refractory magnesium oxide fiber paper with a modified Buna-N phenolic resin, tape wound, with a laminate orientation of 60°. One MXR-42 billet was post-cured and one was not.

e. MX-2600 (two billets tested) - A silica fiber-phenolic resin composite, tape wound, with a laminate orientation of 60°. One MX-2600 billet was post-cured and one was not.

f. MX-5707 (two billets tested) - A low density silica-phenolic composite, tape wound, with a laminate orientation of 60°. One MX-5707 billet was post-cured and the other was not. Both billets were encased in steel sleeves to increase the structural integrity of the material.

g. C-1589-48 with SC1008 (one billet tested) - A silica fiber-phenolic composite in which the silica fibers have been coated with chromic oxide. This material is commonly referred to as "Irish Refrasil" and was constructed by the laminate lay-up method with a laminate orientation of 90°.

h. C-1589-48 with SC1008 and nylon (one billet tested) - A similar material to that of item g, except that the resin system has been modified by the addition of 25 percent nylon. This material was constructed with a laminate orientation of 90° by the laminate lay-up method.

i. Oxidation resistant carbon cloth (one billet tested) - A carbon cloth material treated to improve its oxidation resistance and bonded with a nylon modified phenolic resin. This material has a 90° laminate orientation and was constructed by the laminate lay-up method.

j. SK-5230-119 "A" and "B" (two billets tested) - A filament wound, epoxy resin impregnated silica material. This material exhibits controllable density and thermal conductivity which can be varied both axially and radially during manufacture. This material is knows as Lockheat.

All laminate type billets were tested in the evaluator engine with the plies sloped up and back toward the injector. Detailed specifications on the above materials are as outlined in table 2.

TEST PROGRAM

The test program specified that each ablative material billet should be mounted on the evaluator engine for a continuous firing of three minutes. As a result of the severe material erosion experienced by the first two billets, the firing time for the next four billets was reduced to two minutes. The firing time for the remainder of the billets was increased to three minutes again as a result of subsequent coordination between MSC and TMC.

The billets were fired in the following order:

a. MXS-51

b. MXSE-48

c. MX-2646

d. MX-2646 "A"

e. MX-2646 "B"

f. MXSE-48

g. MXR-42, no post-cure

h. MXR-42, post-cure

i. MX-2600, no post-cure

j. MX-2600, post-cure

k. MX-5707, no post-cure

l. MX-5707, post-cure

m. C-1589-48 with SC1008 only

n. C-1589-48 with nylon and SC1008

o. Oxidation resistant carbon cloth with nylon and SC1008

p. SK-5230-119 "A" Lockheat

q. SK-5230-119 "B" Lockheat

All billets were fired continuously for two or three minutes except billet MX-5707 (post-cure) which failed after 15 seconds of a scheduled three-minute test.

TEST PROCEDURE

Two Advent injectors, S/N 001 and S/N 003, were water flow calibrated and the resulting spray patterns were compared to select one injector to be used with the evaluator engine. The S/N 001 injector was subsequently selected as demonstrating a more symmetrical and uniform spray pattern. The injectors were compared by cold flowing vertically down onto a water surface maintained at a constant level in a clear plastic container. The resulting patterns were photographed through the bottom of the clear container.

A cooling water flowrate of forty gallons per minute was specified by the Marquardt Corporation (TMC) for the nozzle section with an inlet and outlet pressure of ninety and thirty psig respectively. With the aid of a pump the nozzle section was flow checked and it was determined that a flowrate of twenty-five gpm was the maximum obtainable flow with the desired inlet and outlet pressure specified above. It was agreed by TMC and MSC that this flow was sufficient for the test program.

The ablative billets were each weighed to the nearest one-hundredth of a pound prior to testing. Each billet was then installed to form the combustion chamber of the evaluator engine per the installation instructions set forth by the Marquardt Corporation.

Prior to test firing,the nozzle end of the evaluator engine was capped and the engine was pressurized with nitrogen to 135 psig through an extra chamber pressure tap. The sealing joints of the evaluator engine and the walls of the ablative billets were then leak checked with a soap solution.

The detailed instrumentation log for this program is shown in table 3. The instrumentation set-up was identical for all billets except the two Lockheat ablative billets which required the addition of seven temperature channels to record the temperatures from the buried thermocouples provided in these billets. All instrumentation was calibrated prior to the initial firing of each test day and, thereafter, routine checks were conducted prior to and after each firing. A final post calibration was conducted following the last firing of the testing day.

The propellant feed pressure was initially determined with the aid of the water flow calibration curves. As hot firing flow data became available, hot firing flow curves were plotted and used for feed pressure determination.

The post firing procedure entailed the weighing of each billet to the nearest hundredth pound and sectioning each billet for inspection of the char depth and residue material. The two MX-5707 billets were not sectioned due to the metal encasement. The sections of billets were photographed with the throat ends of each billet placed together. The detailed test procedure for this test is outlined in reference 1.

RESULTS AND DISCUSSION

Billet MXS-51 - The Fiberite Corporation: This billet was subjected to a three minute firing on December 6, 1963. During the test heavy ablative material "glassing"* occurred. This material was then transported from the combustion chamber to the evaluator engine throat by the exhaust gas stream. Collection of this material in the engine throat caused a consequent decrease in the engine throat area and an accompanying increase in chamber pressure and decrease in propellant flowrate.

As indicated in table 4 the total billet material weight loss during this three minute firing was 0.03 pounds. The char incurred during the firing was 0.61 inches. Char depth and degree of material glassing are indicated by figure 3.

Billet MXSE-48 - The Fiberite Corporation: Two billets of this material were tested. The first billet was subjected to a three minute firing on December 6, 1963. During this test heavy ablative material "glassing" again caused an increase in chamber pressure and a decrease in propellant flowrate. The total billet material weight loss during the three minute firing was 0.06 pounds. Char depth was 0.69 inches and is shown in figure 4.

Following the three minute firing, the decision was made to vary the propellant feed pressures during the tests to maintain constant propellant mass flowrates which were considered to have a primary effect on material evaluation. It was also decided at this time to reduce the engine firing duration to two minutes to eliminate excessive ablative material buildup in the evaluator engine throat.

The second MXSE-48 billet was tested on January 2, 1964. This billet was subjected to a two minute firing. During the firing it was necessary to adjust the propellant feed pressures to maintain flowrates. The resulting increase in chamber pressure was only a few pounds above the design chamber pressure of 150 psia. The highest increase in chamber pressure as a result of propellant flowrate adjustment during the entire test program was only 9 psig.

The total billet material weight loss for the two minute firing was 0.04 pounds and the resulting char-depth was 0.61 inches.

In comparing the results of the two firings it is noted that a relatively large weight loss difference was incurred compared to a minor difference in char-depth. Specifically, a 33 percent change in weight loss was recorded as compared to a 11.5 percent change in char-depth. It is felt that the increase in weight loss relative to char-depth was a result of expelling a greater quantity of the "glassed" ablative material from the chamber (billet) during the longer firing. Another factor contributing to this condition was the increase in ablating surface area with time during the firing. As the char progresses radially through the billet the char interface surface area increases, thus exposing a larger surface area available for interface ablation and reducing the char-depth penetration rate.

*"glassing" - Formation of molten glass on the I.D. surface as a result of subjecting the silica present in the ablative material to temperatures in excess of 3200°F.

Billet MX-2646 - The Fiberite Corporation: Three billets of this material were tested on January 2, 1964. Each billet was subjected to a firing of two minutes. The three billets represent three different methods of curing during fabrication and are designated as Type "A", Type "B", and "no post-cure".

Although very little ablative material glassing occurred on any of the billets, as shown in figure 5, it was necessary to make minor propellant feed pressure adjustments in order to maintain flowrate during all three tests. The weight losses and char-depths of all three billets are shown in table 4. All three billets performed exceedingly well during these two minute test firings.

Following this series of two minute firings, the decision was made to resume the three minute test durations in order to obtain more exhaustive data on the ablative material billets. This decision essentially eliminated the MX-2646 ablative material from evaluation by comparison to the other materials in this test program due to the varying test period.

Billet MXR-42 - The Fiberite Corporation: Two MXR-42 ablative material billets were tested, one each in the "post-cure" and "no post-cure" condition. These billets were subjected to three minute firings on January 2, 1964. Unlike the preceeding tests, it was not necessary to adjust the propellant feed pressures in order to maintain flowrates during firing for either of these billets. The performance of the evaluator engine was very smooth for both tests, and no agglomeration of ablative material occurred at the engine throat.

The phenolic resin of this material was modified with a Buna-N additive. During testing this modified Buna-N phenolic resin eroded from between the plys of magnesium oxide paper on both billets as shown in figure 6. The use of magnesium oxide paper in lieu of the silica fiber fabric eliminated the problem of ablative material agglomeration at the engine throat. In comparing the performance of billet MXSE-48 with that of MXR-42 it appears that the magnesium oxide reinforcement material has greater resistance to the severe temperature/flow environment than does the silica fiber fabric.

The char-depth was identical on both MXR-42 billets at 0.38 inches, but there was a considerable difference in weight losses. The post-cured billet incurred a weight loss of 0.07 pounds compared to 0.05 pounds for the billet that was not post-cured. This seems to indicate that the post curing process was detrimental to the material. The greater portion of the weight loss during the test can be attributed to resin erosion between the laminates of the magnesium oxide paper as indicated in figure 6. As stated above, magnesium oxide paper exhibited the ability to withstand this type of environment very readily. This material, if combined with the proper bonding system, could possibly produce a superior ablative material.

Billet MX-2600 - The Fiberite Corporation: Two MX-2600 billets, one post-cured and one not post-cured, were subjected to three minute firings on January 2, 1964. It was again necessary to adjust the propellant feed pressures in order to maintain flowrates during the tests as a result of ablative reinforcement material erosion and agglomeration at the engine throat. Figure 7 shows the severe "glassing" condition existing in the billet subsequent to testing.

The post-cured billet evidenced a greater char-depth penetration (0.63 inches) than did the non-post-cured billet (0.56 inches); however, the post-cured billet sustained only a 0.02 pounds reduction in weight compared to 0.03 pounds for the non-post-cured billet. The greater weight reduction associated with the least char penetration for the non-post-cured billet is considered to be the result of expelling a greater quantity of the "glassed" ablative material from the chamber during firing.

Billet MX-5707 - The Fiberite Corporation: Post-cured and non-post-cured billets of this ablative material were subjected to three minute firings on January 2, 1964. The post-cured billet test was terminated after fifteen seconds when the injector end of the ablative chamber burned through. This failure was undoubtedly due to the leakage of exhaust gas from the combustion chamber between the injector plate and billet assembly to the outer case. The engine assembly was leak checked prior to firing, thus it is considered likely that the leak developed during the initial stages of the firing.

The non-post-cured billet was subjected to a firing duration of three minutes during which it was necessary to adjust the propellant feed pressure in order to maintain flowrates due to ablative material agglomeration in the engine throat. This billet sustained a weight loss of 0.16 pounds which was the greatest loss incurred by any of the billets tested.

Neither of the MX-5707 billets were sectioned, as shown in figure 8, since it was considered likely that the material would break up if the steel sleeve was removed. Since the billets were not sectioned it was not possible to obtain measured char-depths.

Billet C-1589-48 with SC1008 - H. I. Thompson Fiberglass Company: This billet was subjected to a three minute firing on January 3, 1964. Although ablative reinforcement material erosion and subsequent throat area restriction again occurred, as was the case with all the silica fiber fabric materials tested, very little propellant feed pressure adjustment was necessary in order to maintain flowrates. This material incorporates a chromic oxide coating on the reinforcement material silica fibers which may have reduced the "glassing" of the billet. The billet incurred a relatively small weight loss of only 0.02 pounds and a char-depth of 0.51 inches.

Billet C-1589-48 with SC1008 and nylon - H. I. Thompson Fiberglass Company: This billet was subjected to a three minute firing on January 3, 1964. Ablative reinforcement material erosion and agglomeration again restricted exhaust gas flow and necessitated continual propellant feed pressure adjustment during the test. The weight loss incurred by this billet was identical to the C-5189-48 billet without nylon (0.02 pounds) but the char-depth was somewhat greater - 0.56 inches. The addition of nylon to the resin system of this billet was an attempt to induce a greater production of gas during the ablative material pyrolysis to effect better cooling and longer material life. Based on the results of this test however the addition of nylon appears to be detrimental to the material. Figure 9 indicates the degree of ablative material agglomeration for the basic material and that containing nylon.

Oxidation Resistant Carbon Cloth - H. I. Thompson Fiberglass Company: This billet was subjected to a three minute firing on January 3, 1964. A large volume of this material was eroded away during the test as shown in figure 10. The chamber pressure steadily declined throughout the test as the chamber volume increased as a result of this material erosion. It was necessary to reduce the propellant feed pressure during the test to prevent the flowrates from becoming too high as the chamber pressure steadily declined.

This material incorporates the same resin system as that used on the C-1589-48 with SC1008 and nylon. No evidence of ablative reinforcement material agglomeration was noted in the oxidation resistant carbon cloth billet as compared to the silica fiber reinforced billets which were highly subject to this "glassing".

The material weight loss of this billet was 0.11 pounds and the char-depth was 0.86 inches.

Lockheat SK-5230-119 - Lockheed Aircraft Corporation: Two billets of this material were tested on January 3, 1964. The billets were designated "A" and "B" and each was subjected to a three minute test. "Glassing" was very severe on both billets as shown in figure 11 and it was necessary to continuously adjust the propellant feed pressures in order to maintain flowrates throughout both tests. This material exhibited the most severe glassing tendency of all ablative materials tested. The weight loss and char-depth for both billets was identical, 0.05 pounds and 0.64 inches.

Each billet was equipped with seven thermocouples buried at various depths within the chamber wall. The thermocouple numbering system and location are shown in figure 12. At shutdown after three minutes of firing, thermocouples numbers 1, 5, 7, and 2 on billet "A" indicated temperatures of 1892°F, 922°F, 332°F, and 152°F respectively. No significant temperature change was recorded on thermocouple numbers 3, 4, and 6 during the three minutes of testing. The temperature profile in the billet is shown on figure 13. A change in the rate of heat transfer at the char interface is indicated by the change in the slope of the curve at that point. This is undoubtedly due to the difference in the heat transfer coefficient in the virgin material as compared to the char.

The number 1 thermocouple on billet "B" burned out after approximately 46 seconds of firing. Thermocouple number 5 indicated a temperature of 602°F at shutdown and the remaining thermocouples indicated only slight temperature change. The temperature data obtained on billet "B" was very limited and was considered inconclusive.

The water cooled throat section of the evaluator engine was originally scheduled to be used as a calorimeter during the tests by recording the water inlet and outlet temperatures. However, with the 25 gpm cooling water flowrate established no temperature changes were recorded.

CONCLUSIONS AND RECOMMENDATIONS

1. Ablative material billet MXR-42 exhibited the best overall performance of all the materials subjected to the three minute firing duration. The magnesium oxide reinforcement fabric utilized in this material held up very well and shows considerable promise for rocket engine application. It is recommended that further testing be accomplished on the magnesium oxide reinforcement fabric combined with various bonding materials.

2. Ablative material billet MX-2646 exhibited satisfactory performance when subjected to a firing duration of two minutes. Further testing should be accomplished on the material to determine its capability to withstand firings of longer duration.

3. Ablative material billet C-1589-48 performed satisfactorily although some "glassing" occurred. The degree of glassing appeared somewhat less than that observed for other silica fabric reinforced materials, and this difference may have been due to the chromium oxide coating of the fibers.

4. The use of nylon in the resin system of ablative billet C-1589-48 does not improve the performance of the material.

5. All ablative materials tested for the full three minute duration which utilized silica fabric reinforcement "glassed" to a relatively severe degree such that propellant mass flowrate was restricted. This material phase change and subsequent agglomeration in the engine throat places all silica fabric reinforcement ablative materials in a questionable position as to usefulness in duration firing rocket engine application. However, selection of materials for rocket engines designed for pulse mode operation will necessitate consideration of additional properties and problem areas outside the scope of this evaluation.

6. The oxidation resistant carbon cloth eroded severely during test. It is recommended that additional development and testing be accomplished on this material if the severe erosion characteristic can be improved.

REFERENCES

1. TTS, Reaction Control Systems Interim Facility Test Procedure No. 009.

2. Schmidt, Donald L., "Ablation of Plastics," USAF Report No. ASD-TR-61-650, February 1962.

3. The Fiberite Corporation, Winona, Minnesota, "The Ablative Thermal Insulation Handbook".

EVALUATOR ENGINE PERFORMANCE

TABLE I

BILLET	CHAMBER PRESSURE (PSIA)	OXIDIZER FLOW (LBS/SEC)	FUEL FLOW (LBS/SEC)	O/F RATIO	THRUST (LBS)	FIRING TIME (MIN.)
MXS-51	148	0.0350	0.0258	1.385	13.7	3
MSE-48	150	0.0381	0.0229	1.660	12.9	3
MX-2646 NPC	154	0.0388	0.0232	1.673	13.2	2
MX-2646 "A"	150	0.3730	0.0246	1.516	12.3	2
MX-2646 "B"	147	0.0371	0.0225	1.649	12.0	2
MXSE-48	149	0.0372	0.0244	1.530	13.0	2
MXR-42 NPC	152	0.0376	0.0236	1.592	12.5	3
MXR-42 PC	151	0.0232	1.6100	1.610	12.0	3
MX-2600 NPC	151	0.0373	0.0234	1.590	12.5	3
MX-2600 PC	152	0.0383	0.0235	1.628	12.0	3
MX-5707 NPC	156	0.0343	0.0219	1.565	12.0	3
MX-5707 PC	THIS CHAMBER BURNED THROUGH ON THE INJECTOR END AFTER APPROXIMATELY 15 SECONDS OF FIRING					
C-1589-48 SC-1008 only T372	153	0.0342	0.0219	1.560	13.0	3
C-1589-48 nylon and SC-1008 T373	155	0.0342	0.0219	1.560	12.0	3
Oxidation re-sistant carbon cloth	155-152	0.0345	0.0213	1.520	12.0	3
Lockheat "A"	152-159	0.0376	0.0236	1.590	12.1	3
Lockheat "B"	151-160	0.0375	0.0236	1.580	12.1	3

TABLE 2

ABLATIVE MATERIAL SPECIFICATIONS

MATERIAL	SPECIFIC GRAVITY	TENSILE STRENGTH PSI @ 72°F	COMPRESSIVE STRENGTH PSI	RESIN TYPE	RESIN SOLIDS CONTENT %	REINFORCEMENT TYPE	REINFORCEMENT %
MXS-51	1.75	12,700	40,000	Fiberite Snap 51 MIL-R-9299	31	Silica Fabric	69
MXSE-48	1.55	7,000		High temperature phenolic MIL-R-9299	30-35	Silica Fabric	65-70
MX-2646	1.79	13,000	36,000	Polyamide modified phenolic-high temperature	18-22	Silica Fabric	78-82
MXR-42	PC 1.72 NPC 1.75	11,000	16,700	Buna-N modified phenolic	28-32	Magnesium oxide paper	68-70
MX-2600	NPC 1.76 PC 1.743	14,000	N/A	High temperature phenolic MIL-R-9299	29-33	Silica Fabric	67-71
MX-5707	1.15	7,500	12,500	High temperature phenolic	39.5-45	Silica Fabric	60.5-55
C1589-48 plus SC 1008	1.77	N/A	N/A	Monsanto SC 1008 phenolic resin		Silica Fabric coated with chromic oxide	
C1589-48 plus nylon and SC 1008	1.78	N/A	N/A	Monsanto SC1008 with 25 percent nylon phenolic resin		Silica Fabric coated with chromic oxide	
Oxidation Resistant Carbon Cloth	1.225	N/A	N/A	Monsanto SC 1008 plus 25 percent hylon		Carbon Fiber	
Lockheat	1.51			Epoxy		Silica Fiber	

INSTRUMENTATION LOG

TABLE 3

PARAMETER	TRANSDUCER	JB1	JB2	AMPLIFIER	OSCILLOGRAPH 1	OSCILLOGRAPH 2	TRACE	CALIB. DATA
REFERENCE							1	
Water inlet	CA/TC	1	1	10	Channel 1 (316)		2	$\pm 2^{\circ}$
Water outlet	CA/TC	2	2	11	Channel 2 (316)		3	5 - 10 T
Water outlet	CA/TC	3	3	12	Channel 3 (316)		4	" " "
Injector	CA/TC	4	4		Channel 4 (343)		5	500 - 1000°
*Billet No. 1	CA/TC	5	5		Channel 5 (343)		6	Up to 3300°F
*Billet No. 2		6	6		Channel 6 (343)		7	
*Billet No. 3		7	7		Channel 7 (343)		8	
*Billet No. 4		8	8		Channel 8 (343)		9	
*Billet No. 5		9	9		Channel 9 (343)		10	
*Billet No. 6		12	12		Channel 10 (343)		12	
*Billet No. 7	CA/TC	13	13		Channel 11 (343)		12	
Fire Volt					Channel 18 (361)		13	
Skin	CA/TC	10	10		S.C. No. 1 (Red)			Front
Skin	CA/TC	11	11		S.C. No. 2 (Purple)			Back

*On 2 Lockheat billets

1.8 lPS Timing 4
Galvo 2 Low Range

TABLE 3 (CONTINUED)

PARAMETER	TRANSDUCER	JB1	JB2	AMPLIFIER	OSCILLOGRAPH 1	OSCILLOGRAPH 2	TRACE	CALIB. DATA
REFERENCE							1	
Thrust	ALINCO 335738	1	1	9		Channel 2 (316) S.C. No. 2 (black)	2	5,10,15.2, 20.1,28.2, 30,35
Chamber Press.	TABER 33465	6	6	5		Channel 3 (316) S.C. No. 2 (blue)		22,67,45.34, 68.5,90.7, 113.35
Water inlet pressure	TABER 63315	2	2	6		Channel 4 (326)	4	21.2,42.5, 64.2,85
Fuel Inj. pressure	TABER 633426	3	3	7		Channel 5 (316)	5	42.6,85.3,128.9 170.67,213.35
Ox. Inj. pressure	TABER 633152	4	4	8		Channel 6 (316)	6	42.5,83,128.3, 170,212.4,254
Fire volt						Channel 13 (361)	7	
Fuel Prop Valve current						Channel 14 (326)	8	
Ox. Prop Valve current						Channel 15 (326)	9	
Fuel flow						Channel 16 (326)	10	
Ox. Flow						Channel 17 (326)	11	
Timing						Channel 18 (326)	12	
Fuel flow analog						S.C. No. 2 (red)		
Ox. Flow analog						S.C. No. 2 (green)		

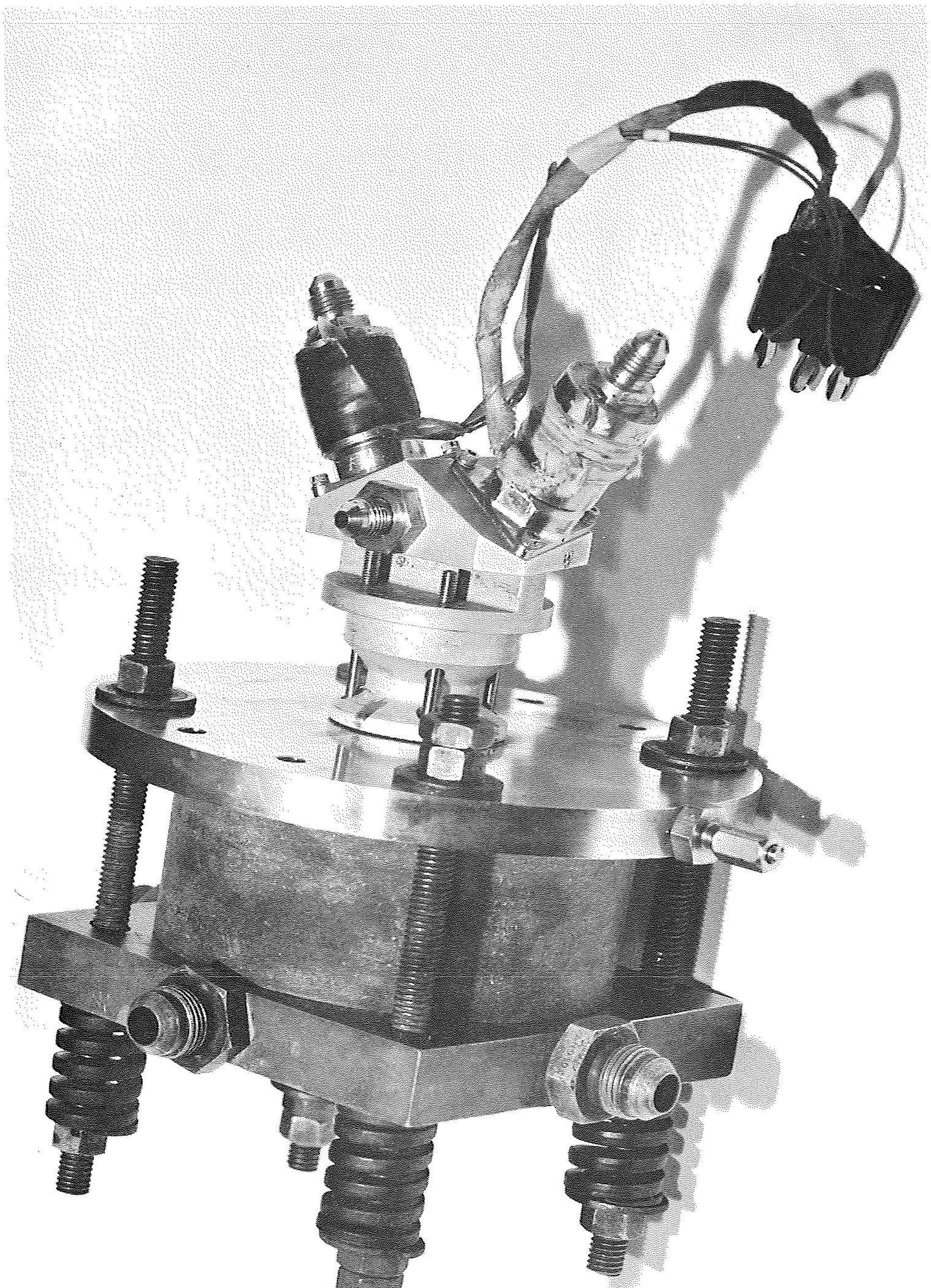
ABLATIVE BILLET PERFORMANCE DATA

TABLE 4

BILLET	PRE-FIRE WT. (LBS)	POST-FIRE WT. (LBS)	WEIGHT LOSS (LBS)	CHAR DEPTH (INCHES)	% WEIGHT LOSS
MXS-51	1.70	1.67	0.03	0.61	1.76
MXSE-48	1.71	1.65	0.06	0.69	3.5
MX-2646 NPC*	2.02	1.99	0.03	0.52	1.48
MX-2646 "B"*	2.00	1.98	0.02	0.52	1.0
MX-2646 "A"*	2.00	1.98	0.02	0.51	1.0
MXSE-48* (2 min)	1.70	1.66	0.04	0.61	2.35
MXR-42 NPC	1.93	1.88	0.05	0.38	2.59
MXR-42 PC	1.90	1.83	0.07	0.38	3.68
MX-2600 NPC	1.93	1.90	0.03	0.56	1.55
MX-2600 PC	1.91	1.89	0.02	0.63	1.04
MX-5707 PC	2.55	2.44	Did not fire full duration		
MX-5707 NPC	2.79	2.63	0.16	N/A	5.73
C1589-48 + SC 1008	1.96	1.94	0.02	0.51	1.02
C1589-48 + nylon and SC 1008	1.97	1.95	0.02	0.56	1.01
Carbon cloth	1.54	1.43	0.11	0.86	7.14
Lockheat "A"	1.51**	1.46	0.05	0.64	3.31
Lockheat "B"	1.51**	1.46	0.05	0.64	3.31

*NOTE: Billet subjected to 2 minute firing only.

**NOTE: Lockheat billets were weighed with thermocouple wires and connectors.



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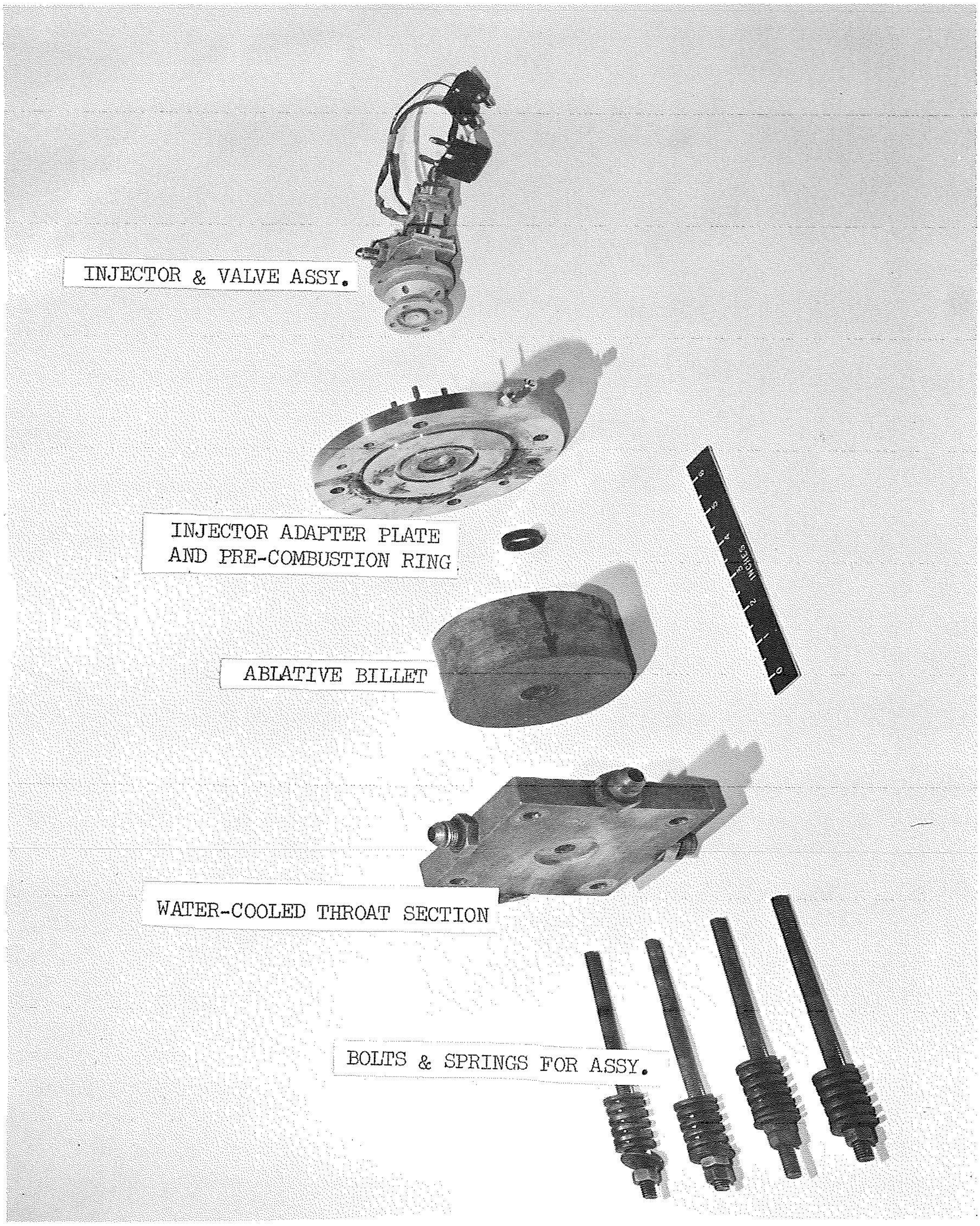
ASSEMBLED EVALUATOR ENGINE

FIGURE 1



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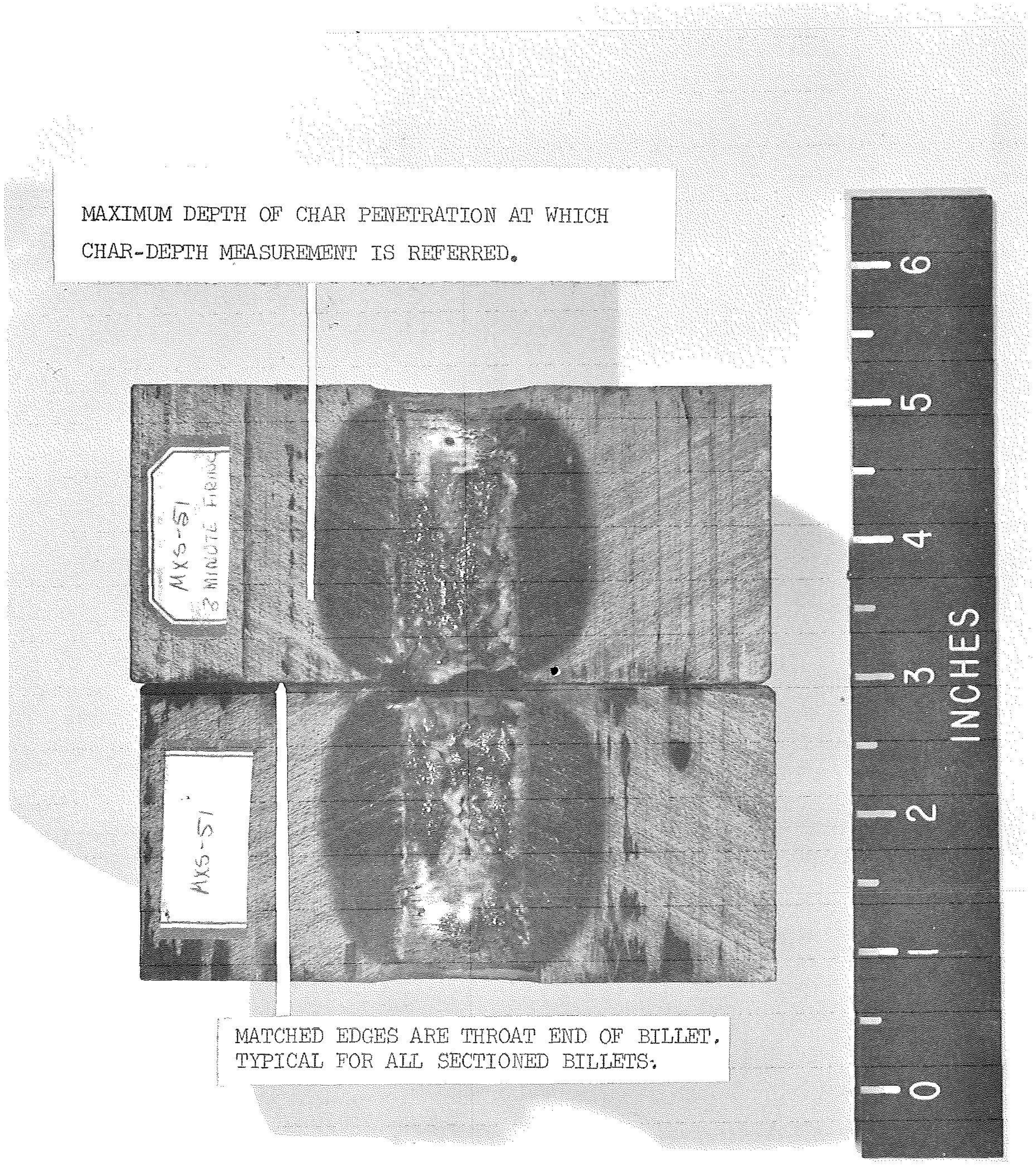
EVALUATOR ENGINE COMPONENTS

FIGURE 2



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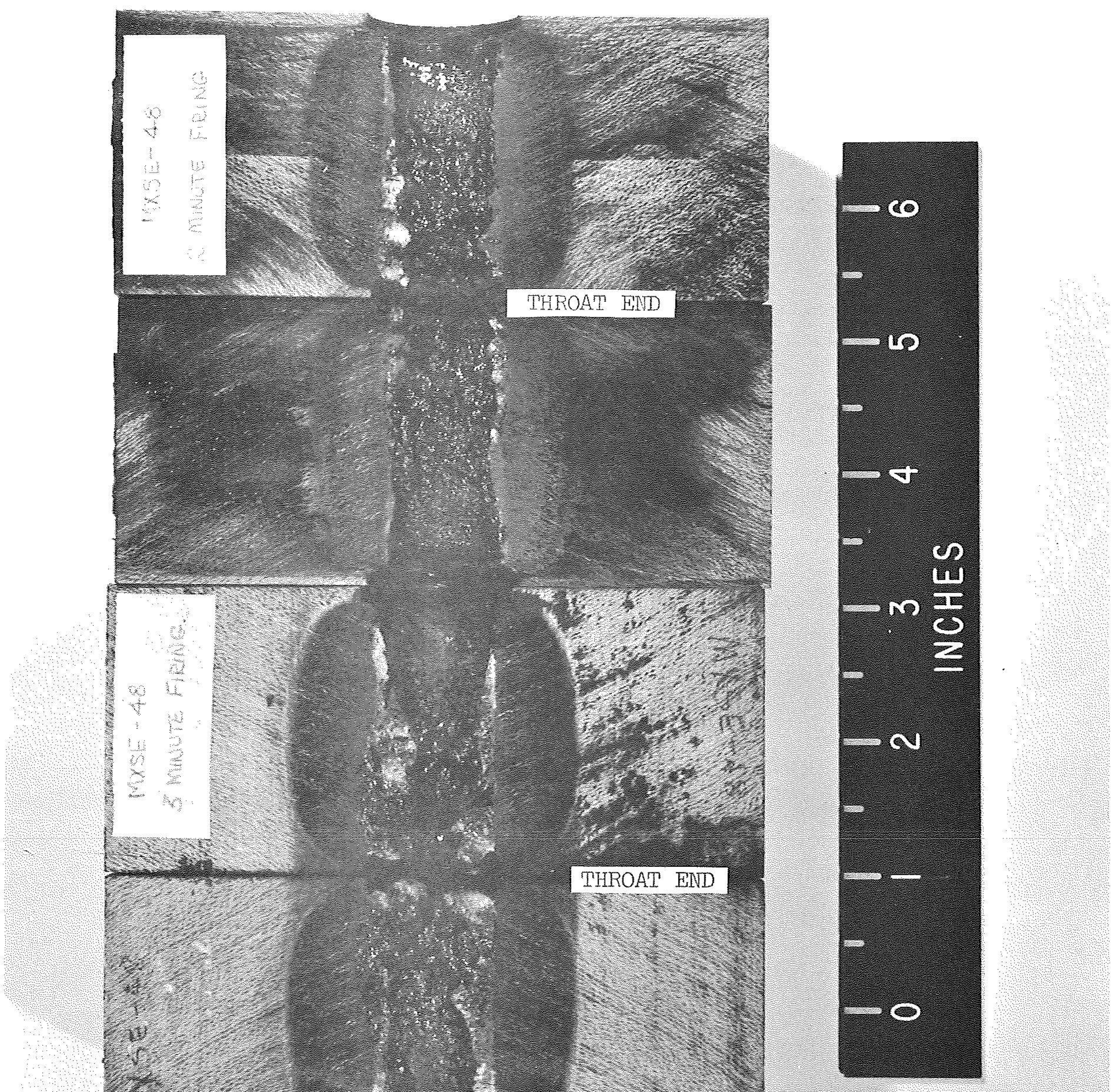
MXS-51 BILLET

FIGURE 3



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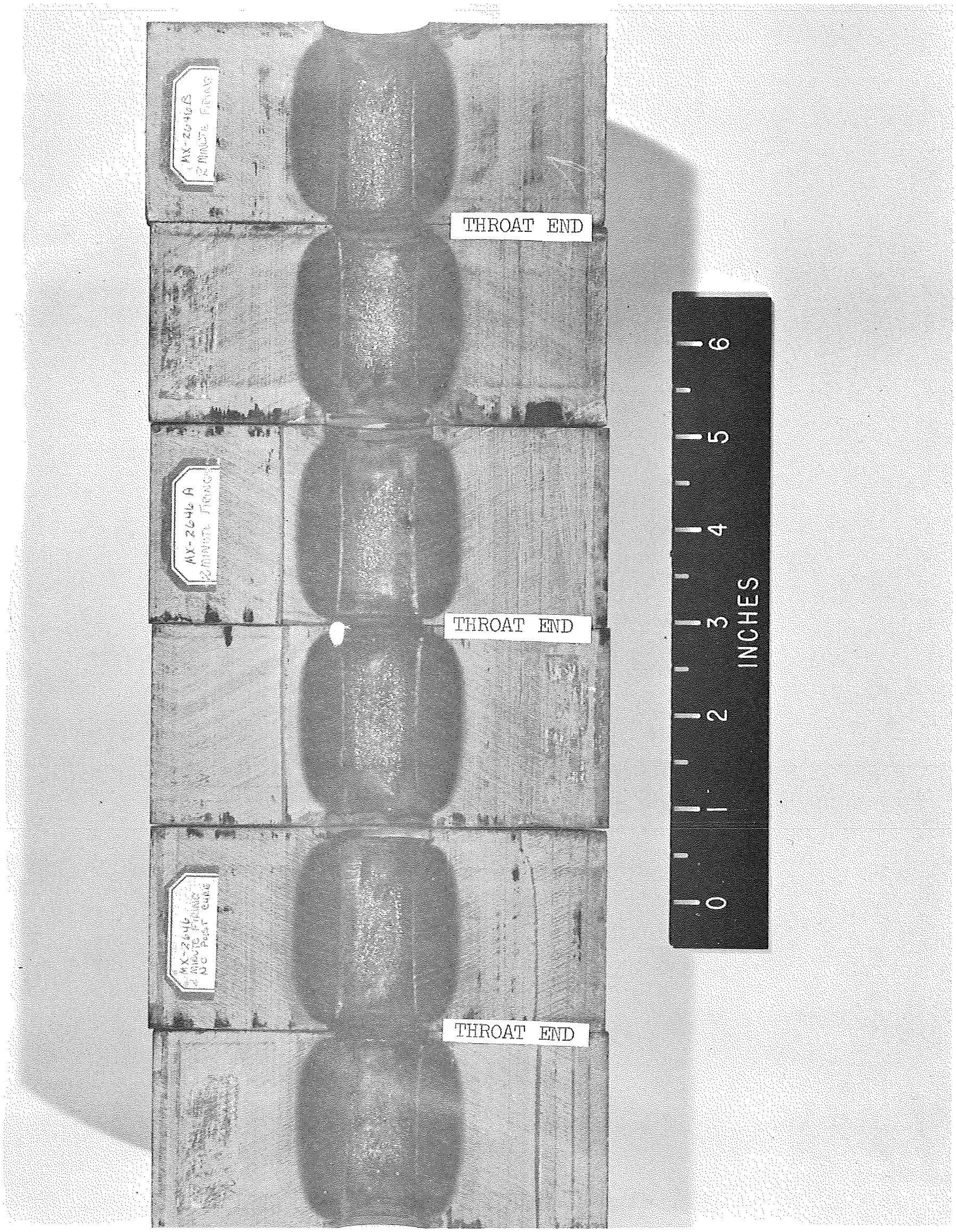
MXSE-48 BILLETS

FIGURE 4



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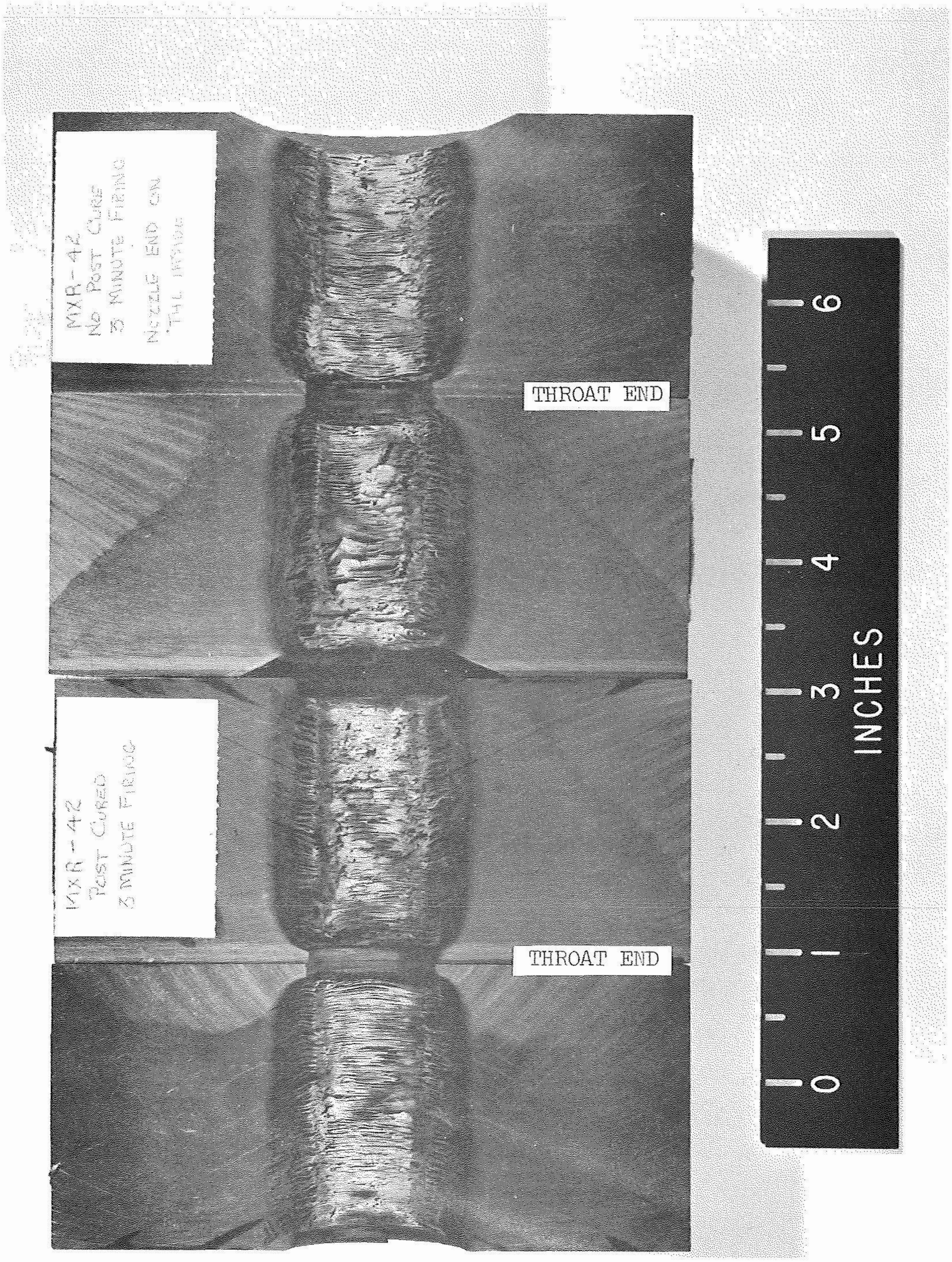
MX-2646 BILLETS

FIGURE 5



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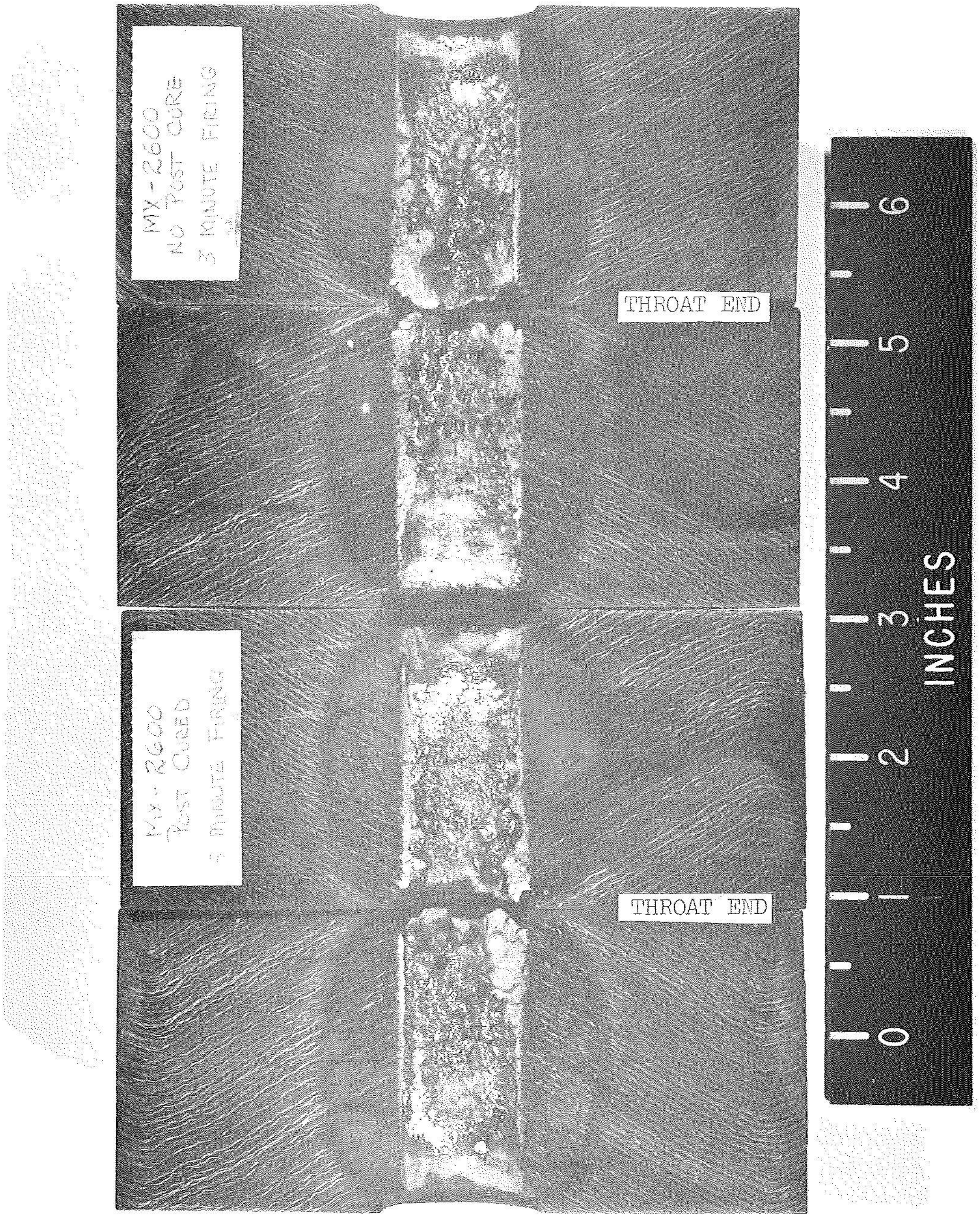
MXR-42 BILLETS

FIGURE 6



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MX-2600 BILLETS

FIGURE 7

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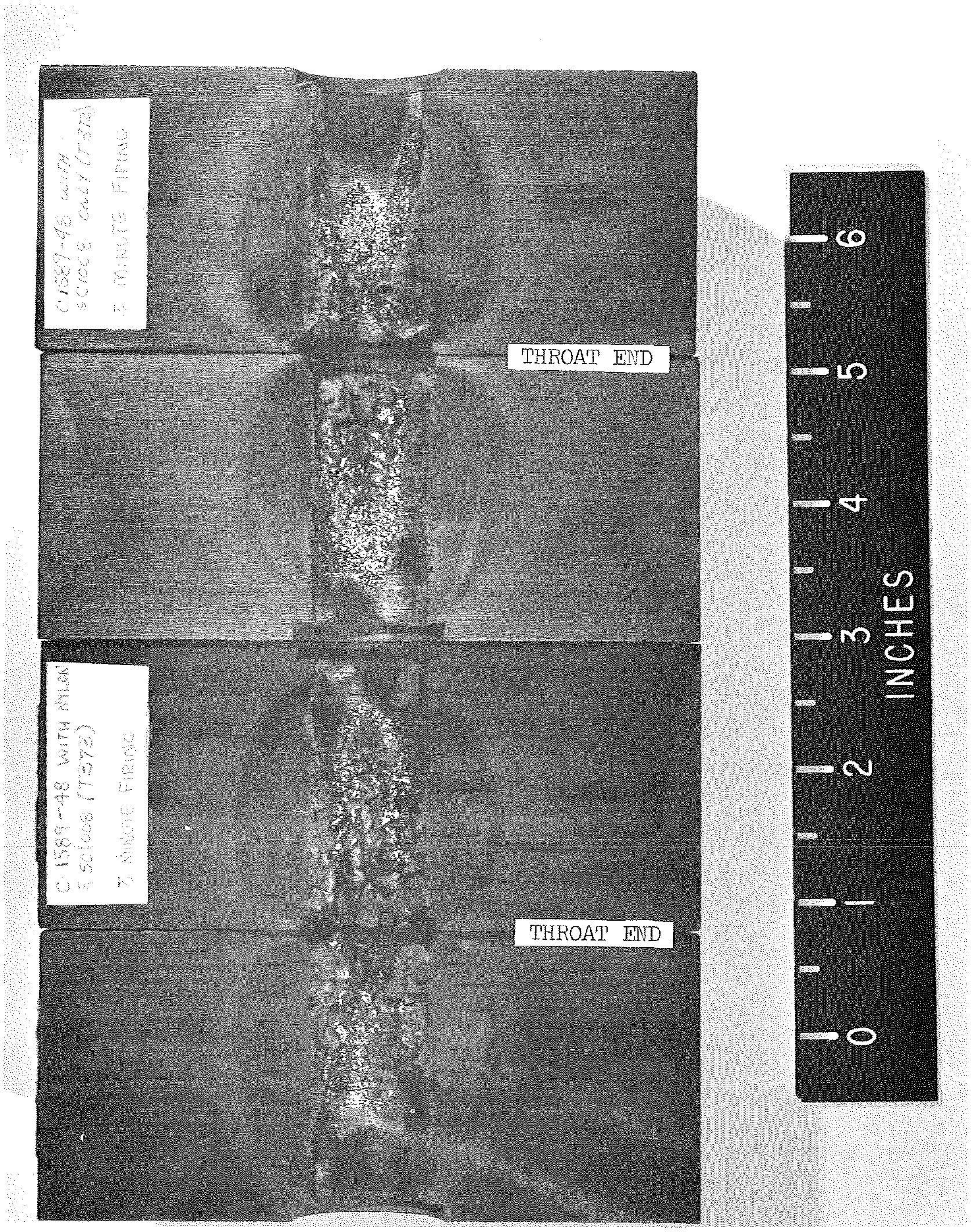
POST-CURE BILLET

NO POST-CURE BILLET

MX-5707 BILLETS

FIGURE 8



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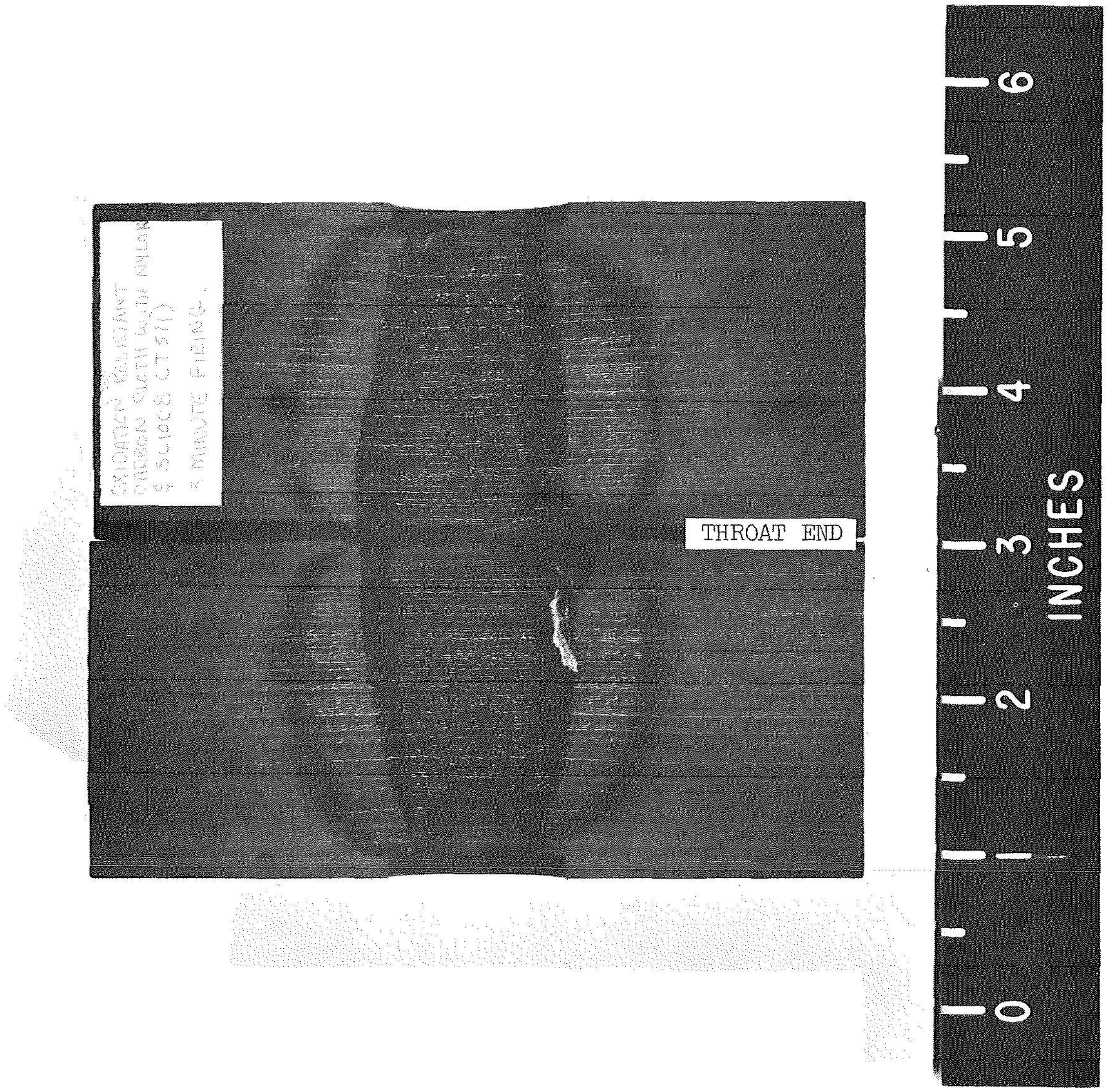
C1589-48 BILLETS

FIGURE 9



OXIDATION RESISTANT CARBON CLOTH
FIGURE 10

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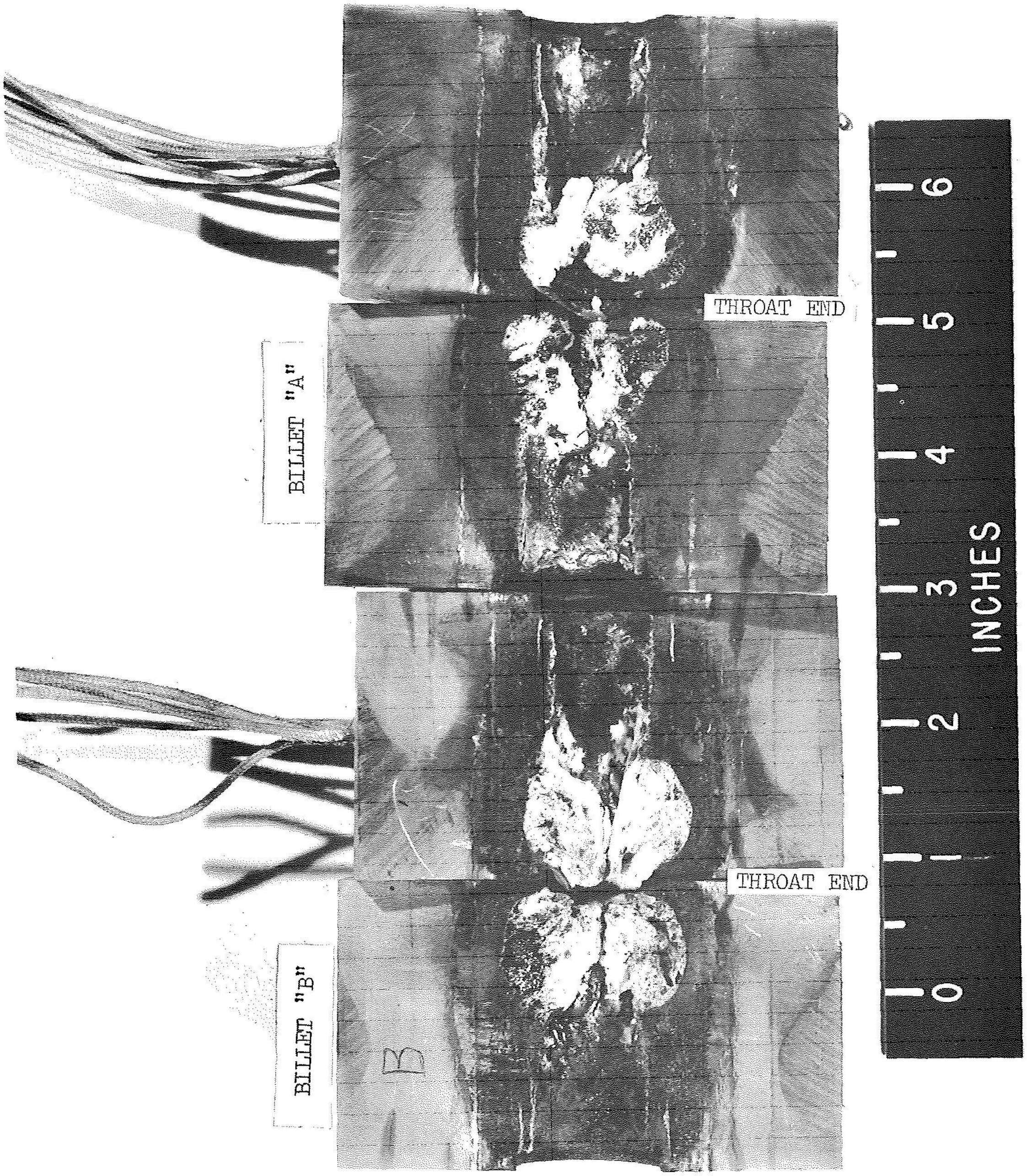

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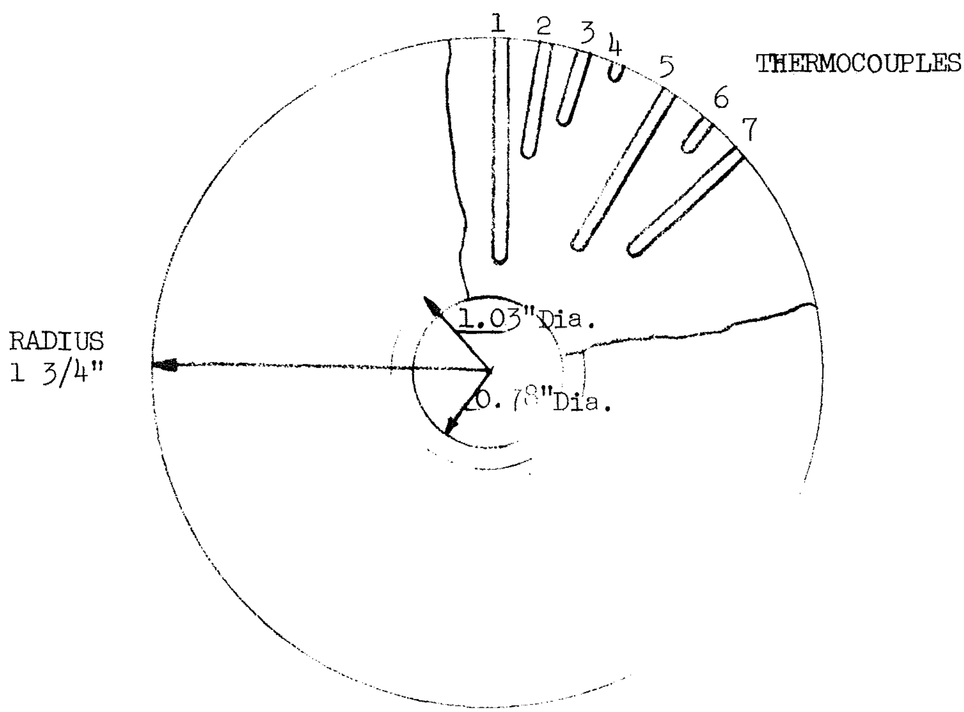
LOCKHEAT BILLETS

FIGURE 11

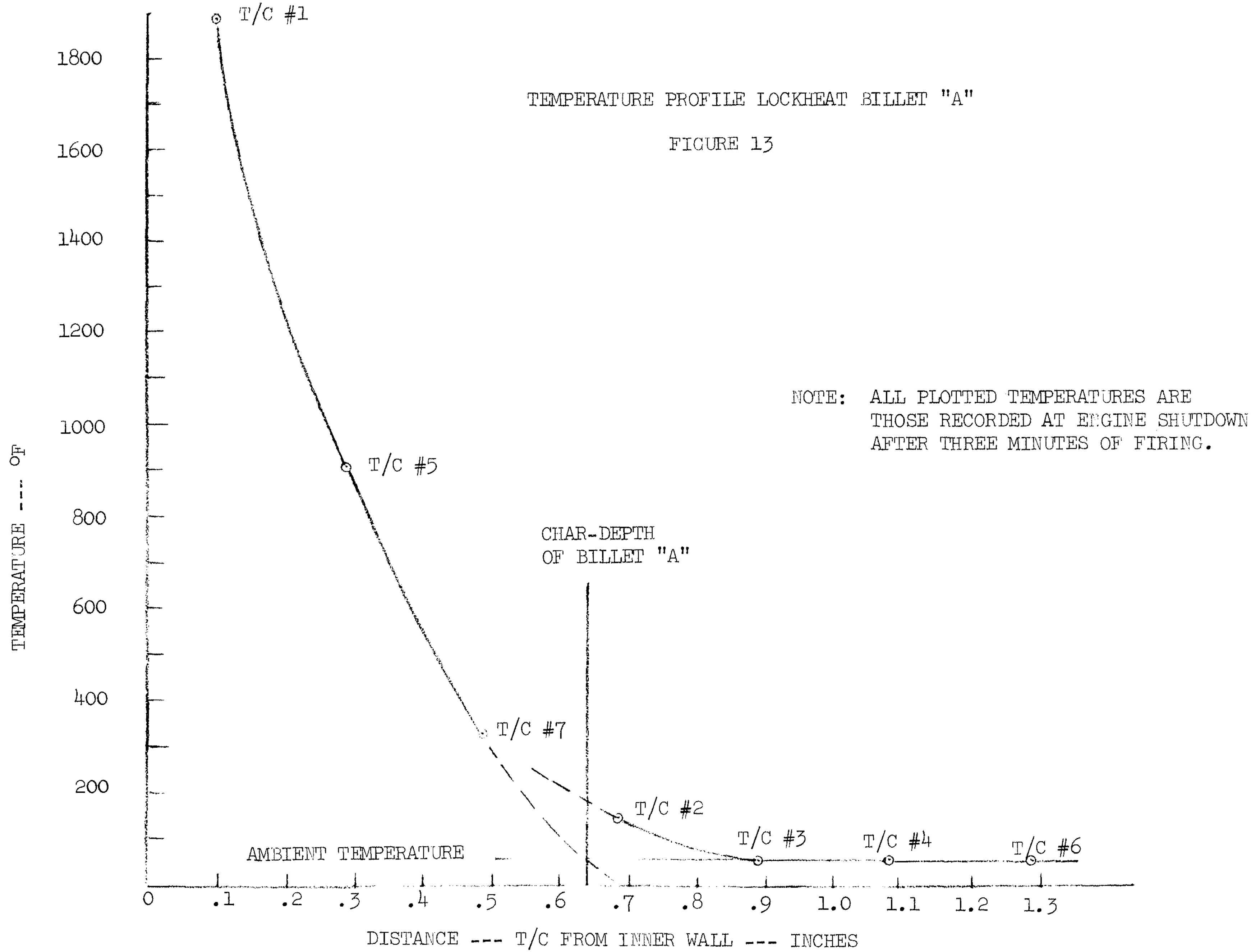


DISTANCE FROM THERMOCOUPLE TO CHAMBER WALL

NO. 1 - 0.09"
NO. 2 - 0.69"
NO. 3 - 0.89"
NO. 4 - 1.29"
NO. 5 - 0.29"
NO. 6 - 1.09"
NO. 7 - 0.49"

LOCKHEAT THERMOCOUPLE ARRANGEMENT

FIGURE 12



TEMPERATURE PROFILE LOCKHEAT BILLET "A"

FIGURE 13